The palaeoenvironmental development of the northeastern Vietnamese Mekong River Delta since the mid Holocene

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Abstract

Three radiocarbon-dated sediment cores from the northeastern Vietnamese Mekong River Delta have been analysed with a multiproxy approach (grain size, pollen and spores, macro-charcoal, carbon content) to unravel the palaeoenvironmental history of the region since the mid Holocene. During the mid-Holocene sea-level highstand a diverse, zoned and widespread mangrove belt (dominated by *Rhizophora*) covered the extended tidal flats. The subsequent regression and coeval delta progradation led to the rapid development of a back-mangrove community dominated by *Ceriops* and *Bruguiera* but also represented locally by e.g. *Kandelia*, *Excoecaria* and *Phoenix*. Along rivers this community seems to have endured even when the adjoining floodplain had already shifted to freshwater vegetation. Generally this freshwater vegetation has a strong swamp signature but locally Arecaceae, Fabaceae, Moraceae/ Urticaceae and Myrsinaceae are important and mirror the geomorphological diversity of the delta plain. The macro-charcoal record implies that natural burning of vegetation occurred throughout the records, however, the occurrence of the highest amounts of macro-charcoal particles is linked with modern human activity.

Keywords

Holocene, macro-charcoal, modern human impact, palaeoenvironment, pollen, Vietnamese Mekong River Delta

Introduction

The Mekong River Delta in southern Vietnam and southern Cambodia is formed by the Mekong and Bassac River systems and extends over an area of 62 520 km² today (Nguyen *et al.*, 2000). The oldest sediments, which are linked to the modern delta body, accumulated in the early mid-Holocene at about 8000 calibrated years before present (cal. yr BP) (Tamura *et al.*, 2009) preceding the mid-Holocene sea-level highstand in the South China Sea. In the case of the Mekong River Delta (MRD, in the following used as abbreviation for the Vietnamese part of the Mekong River Delta unless stated otherwise, the term ‘delta’ refers the Cambodian and Vietnamese Mekong River Delta) area, the highstand of c. 2.5 to 4.5 m above present sea level lasted from c. 6000 to 5000 cal. yr BP (Ta *et al.*, 2002a, b). In this phase the coastline was located in modern southern Cambodia (Nguyen *et al.*, 2000; Tamura *et al.*, 2009) and is generally referred to as marking the most landward margin of the delta body (Woodroffe *et al.*, 2006). Pollen records as well as peat horizons imply that a broad mangrove swamp covered the coastal zone in the mid Holocene (Penny, 2006, 2008; Tamura *et al.*, 2009). The subsequent regression together with a large sediment discharge (since 3000 cal. yr BP: $144 \pm 36 \times 10^6$ t/yr, Ta *et al.*, 2002b) enabled the fast progradation of the MRD (Nguyen *et al.*, 2000).

Today the delta is one of the megadeltas in Asia that is intensively used for agriculture, forestry and fishery by 17 million people (Mekong River Commission, 2005). The agricultural use of the delta plain has a long history but the large-scale, intensified

rice farming by the Vietnamese, which form the majority of the population in the MRD today, started in the seventeenth century (Biggs, 2003). Together with Chinese settlers Vietnamese people started to migrate into the relatively sparsely populated delta area and expanded the rice paddies during the 1600s (Biggs, 2003; Biggs *et al.*, 2009). Until the eighteenth century, however, agriculture centred along large rivers and creeks (Biggs, 2003). With the major canal excavations in the eighteenth and nineteenth centuries the water balance on the MRD plain became easier to control and opened new areas for settlement and agriculture (Biggs, 2003; Kono, 2001). Some marginal swamp areas such as the Dong Thap Muoi (or Plain of Reeds, Figure 1) remained widely uninhabited until after 1975 when further canal excavations promoted the

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development of extensive rice cultivation (Kono, 2001; Nguyen *et al.*, 1998; Tanaka, 2001).

The palaeoenvironmental development of the MRD has been the focus of only few studies so far. In the western and southern parts of the MRD, the change from mid-Holocene mangrove to late-Holocene freshwater vegetation varied temporally and spatially (Nguyen, 1993). According to Nguyen (1993) the major factors for this variance are local differences in topography, water balance and substrate. In the northeastern MRD, however, the palynological signal in the sedimentary record implies that mangroves seem to have vanished relatively abruptly (Proske *et al.*, 2010). However, some saltwater-tolerant vegetation, in particular back-mangrove communities, could have prevailed longer in the area mainly along major rivers (Fujimoto *et al.*, 2008). During the late Holocene, indigenous freshwater vegetation was at least in parts dominated by a tropical forest as the discovery of large tree stumps implies (Sterling *et al.*, 2006). This forest would certainly resemble the forest types adjoining the modern delta: a mix of evergreen, semi-evergreen (dominated by *Lagerstroemia*), deciduous and coastal forests that are often dominated by Dipterocarpaceae (Duc, 2006; Schmid, 1974, 1989; Sterling *et al.*, 2006).

With the conversion of the land for large-scale occupation and agriculture the indigenous vegetation became restricted to very local patches (Tanaka, 2001). Besides the cultivated areas that are mainly covered by rice (*Oryza sativa japonica*), sugarcane (*Saccharum officinarum*), pineapple (*Ananas comosus*), coconut (*Cocos nucifera*) and banana (*Musa × paradisiaca*) (Hori, 2000), three main forms of natural vegetation remain in the modern MRD: freshwater swamp forest and freshwater grasslands (U Minh region, Plain of Reeds and Ha Tien Plain) as well as mangrove (along major parts of the coast) (Sterling *et al.*, 2006).

An overview over the major relevant freshwater families and their habitat is given in Table 1. The modern freshwater swamp forests are most common in the Plain of Reeds where the permanently water-logged soils offer ideal conditions for the dominant tree *Melaleuca cajuputi* (Sterling *et al.*, 2006). These forests are adjoined by swamps and grasslands that include grasses (particularly *Echinochloa crus-galli*, *Eriochloa procera*, *Oryza rufipogon*), sedges (mainly *Cyperus elatus*, *Cyperus polystachos*, *Eleocharis dulcis*), ferns (e.g. *Marsilea minuta*), aquatic plants (predominantly *Nelumbium nelumbo*, *Nymphaea* sp.) and *Melaleuca leucodendron*. On elevated areas (e.g. levees) *Lagerstroemia speciosa*, *Ficus microcarpa*, *Elaeocarpus* sp., *Morinda persicifolia* as well as Dipterocarpaceae can be found (Duc, 2006). Along major rivers smaller stands of e.g. *Barringtonia acutangula*, *Terminalia chabula*, and *Diospyros cambodiana* are observed (Duc, 2006).

The composition of the mangrove community varies depending on the amount of freshwater input. An overview of mangrove genera and their appearance within the different zones of the mangrove forest is given in Table 2 (Hong 2000; Hong and San, 1993; Schmid, 1974; Tomlinson 1994). Generally, the estuarine successions are dominated by *Sonneratia*, *Avicennia*, *Rhizophora*, *Ceriops*, *Bruguiera*, *Phoenix paludosa* and the fern *Acrostichum aureum* but can additionally host *Acanthus ilicifolius*, *Flagellaria indica*, *Melastoma polyanthum* and *Dalbergia candanensis*. (Hong, 2000; Hong and San, 1993). The saltwater successions are dominated by *Sonneratia*, *Rhizophora*, *Xylocarpus*, *Ceriops*, *Avicennia*, *Excoecaria agallocha* and *Phoenix paludosa* (Hong, 2000; Hong and San, 1993).

Table 1. Freshwater genera

Family	Genus	R/E	F	Sh	St	FS	Sat	Ap	Aq	An
Alismataceae	<i>Sagittaria</i>								X	
Arecaceae	excl. <i>Nypa</i> & <i>Phoenix</i>		X	X		X				X
Asclepiaceae	–		X		X					
Asteraceae	–		X	X		X				
Aquifoliaceae	<i>Ilex</i>		X	X						
Burmanniaceae	<i>Burmannia</i>					X				
Chenopodiaceae/	–				X					
Amaranthaceae										
Combretaceae	–		X							
Cyperaceae	–	X	X	X	X	X		X		
Elaeocarpaceae	–	X	X			X				
Euphorbiaceae	–		X	X			X	X		
Fabaceae	–	X	X	X	X	X	X	X		X
Fagaceae	–		X	X						
Melastomataceae	–		X	X	X	X		X		
Moraceae	–		X	X		X	X			
Myrsinaceae	–		X	X						
Myrtaceae	–		X			X				
Orchidaceae	–		X			X				
Pandanaceae	<i>Pandanus</i>		X			X				X
Pinaceae	<i>Pinus</i>		X							
Piperaceae	–		X	X						
Poaceae	–	X	X	X	X	X	X	X		X
Sapindaceae	–		X	X						
Urticaceae	–		X							
Azollaceae	<i>Azolla</i>								X	X
Polypodiaceae	–	X	X			X				
Pteridaceae	<i>Acrostichum</i>	X								

R/E, river/estuary; F, forest general; Sh, shrubland; St, steppe; FS, freshwater swamp; Sat, sandy terrace; Ap, alluvial plain; Aq, aquatic; An, anthropogenic.

This paper presents three sedimentary successions showing the palaeoenvironmental development of the northeastern MRD in the last c. 8000 years. It also addresses the regional diversity of the vegetation and mangroves in particular and it documents the impact of modern human settlement on the regional environment.

Study area

The northeastern part of the MRD (Figure 1) is only elevated 0.5 to 1.5 m above modern sea level (Duc, 2006; Nguyen *et al.*, 1998) which has consequences for the water balance, soil characteristics and thus vegetation. Generally the water balance in the delta is controlled by river discharge (varying seasonally with high discharges during the summer monsoon) and the tidal amplitude of 3.0–3.5 m in the South China Sea (Mekong River Commission, 2005). The delta area has an average annual precipitation of 1000–2000 mm falling mainly between April and October (Nguyen *et al.*, 1998) when the whole Mekong River basin is subjected to the summer monsoon (Hori, 2000). This rainfall together with excess river water causes up to a four-month long inundation in the northeastern part of the MRD (Hori, 2000).

Material

Sediment core characteristics

The sediment cores TD08-01 (TD), GD07-01 (GD) and TA07-01 (TA) have been hand-drilled (Edelmann and D-section auger) during two campaigns to Long An province, northeastern MRD in March 2007 and December 2008.

Table 2. Mangrove genera

Family	Genus	Seaward margin	Inner mangrove	Back mangrove	Landward edge	River/estuary
Myrsinaceae	<i>Aegiceras</i>	X				
Sonneratiaceae	<i>Sonneratia</i>	X	X			
Rhizophoraceae	<i>Rhizophora</i>		X	X		
Acanthaceae	<i>Acanthus</i>		X	X		
Avicenniaceae	<i>Avicennia</i>		X	X		
Rhizophoraceae	<i>Ceriops</i>		X			
	<i>Bruguiera</i>		X			
Meliaceae	<i>Xylocarpus</i>		X	X		
Rhizophoraceae	<i>Kandelia</i>			X		X
Sterculiaceae	<i>Heritiera</i>			X		
Euphorbiaceae	<i>Excoecaria</i>			X		
	<i>Glochidion</i>			X		
Flagellariaceae	<i>Flagellaria</i>			X		
Combretaceae	<i>Lumnitzera</i>			X		
Araceae	<i>Cryptocoryne</i>			X	X	
Annonaceae	<i>Annona</i>			X	X	
Flagellariaceae	<i>Flagellaria</i>			X	X	
Arecaceae	<i>Phoenix</i>				X	
	<i>Nypa</i>				X	X
Fabaceae	<i>Dalbergia</i>				X	
Melastomataceae	<i>Melastoma</i>				X	
Pteridaceae	<i>Acrostichum</i>			X		X

Figure 1. (A) The Vietnamese Mekong River Delta and adjacent areas with its two major rivers, the Bassac and the Mekong. The smaller inset map displays the position of the delta within mainland Southeast Asia. The black square marks the area shown in (B). (B) The facies distribution and geomorphological features in the study area according to Nguyen et al. (2000). The open circles show the coring locations of cores GD, TD and TA. The dashed circle outlines the approximate extent of the Plain of Reeds

Core TD. The drilling site (10°39.731'N, 106°12.928'E, Thanh Hoa district) lies in a meander loop within the floodplain of the Vam Co Tay River in the Plain of Reeds (Figure 1B). The core top lies c. 0.5 to 1 m above modern sea level. The uppermost 29 cm consisting of hard clay were too compacted to be drilled with the D-section corer and had to be removed. The complete 516 cm long core consists of dark greyish brown to brownish and

very dark grey mud (clay + silt) with few yellowish-red mottles at the top.

Core GD. The coring site (10°40.216'N, 105°51.651'E, Tan Thanh district) is located in the central Plain of Reeds bordering a long channel (Figure 1B). The top of the core is c. 0.5 to 1 m above modern sea level. The 465 cm long core consists of dark grey to

Table 3. Age data

Core	Sample (cm core depth)	Uncalibrated age (yr)	Specific reservoir correction ΔR	Calibrated age (2 σ -range) (yr BP)	Dated material	Lab. code
TD	132–134	2775 $\pm$ 35	–	2790–2950	Plant remains	Poz-30916
	177–179	5385 $\pm$ 35	–	6020–6280	Plant remains	Poz-30915
GD	80	5590 $\pm$ 40	–	6300–6440	Plant remains	Poz-30910
	112	4650 $\pm$ 40	–	5310–5470	Plant remains	Poz-30911
	167	5570 $\pm$ 35	–	6290–6410	Plant remains	Poz-21312
	213	6040 $\pm$ 40	–	6780–7000	Plant remains	Poz-21313
TA	335	4420 $\pm$ 35	–70 $\pm$ 30	4440–4820	Carbonate shells	Poz-21507
			–23 $\pm$ 56			

greyish brown mud except for a sandy section from ~170 to ~90 cm. From 380 to 360 and 130 to 0 cm numerous yellowish–reddish mottles and concretions occur.

Core TA. The drilling site (10°31.432'N, 106°23.189'E) is close to the town Tan An, bordering a maize field in the vicinity of the Vam Co Tay River floodplain (Figure 1B). The core top lies *c.* 1.0 to 1.5 m above modern sea level. The 340 cm long core consists of brownish to greyish mud except for a dark grey to bluish sandy section between 340 and 196 cm. From 238 cm to the top numerous brownish–yellow concretions and mottles occur.

Methods

Sediment analysis

Sediment samples were taken in the field based on the visual core description (TD: 86 samples (2 cm thickness), GD: 26 (5 cm thickness) and TA: 14 (5 cm thickness)). Additionally, material suitable for radiocarbon dating was extracted and stored separately. In the laboratory one-half of each sample was freeze-dried and *c.* 1 g was used for total carbon measurements (TC, LECO combustion). Only TC was measured since the detection of carbonate in organic-rich sediments by LECO-combustion yields large errors. The rest of each sample was wet-sieved at 63 μ m. Samples with a distinct portion >63 μ m were further sieved at 125, 250, 500 and 1000 μ m.

Radiocarbon dating

Seven samples of selected organic fragments (wood/plant remains) or carbonate shells (Table 3) were submitted for radiocarbon dating at the Poznań Radiocarbon Laboratory, Poland. The calibration was accomplished by Calib version 5.0.1 (Stuiver and Reimer, 1993) using the terrestrial record for the organic fragments (intcal04) and the marine record for the shells (marine04). An ocean-specific, local reservoir effect based on two calibration points for southern Vietnam has been calculated in Calib and used for the calibration of the marine material (Table 3). However, since all the dated carbonate shells originate from shallow-water organisms, there are still some uncertainties in the local reservoir age. In the following the 2 σ -range of all samples is used in order to account for the variance of the calibration curve in the covered time span (Table 3).

Pollen, spore and charcoal analysis

For pollen and spore analysis 29 (TD), 23 (GD) and 16 (TA) samples were prepared at the Department of Palynology and Climate Dynamics, University of Göttingen, Germany. Samples of 0.5 cm³ of the raw,

cooled sediment was processed with the standard pollen analytical techniques including HCl treatment and acetolysis (Faegri and Iversen, 1989). Prior to the chemical treatment one *Lycopodium* tablet was added to each sample in order to calculate the pollen concentration (grains/cm³). The residue of each sample was mounted on slides with glycerol and at least 200 pollen grains per slide were counted at 400 $\times$ magnification. Identification of pollen and spores was accomplished by reference pictures (APSA Members 2007; Huang, 1972; Roubik and Moreno, 1991; Thanikaimoni, 1987). Pollen diagrams were created using the commercial programme Grapher 5. The total pollen sum was used to calculate percentages of all taxa and bases on all taxa excluding aquatics and spores. The pollen zones were defined using a 50% and a 10% threshold of the dominating component (primarily *Rhizophora*) following studies on pollen abundance in deposits beneath mangrove forests and adjoining communities (Blasco, 1984; Hofmann, 2002; Li *et al.*, 2008; Rowe, 2005; Somboon, 1990). The arrangement of the pollen genera and family was based on their occurrence within the mangrove forest from seaward margin on the right to landward margin on the left (cf. Table 2). Freshwater vegetation families were arranged according to their abundance.

Macroscopic charcoal was preferred over microscopic particles since large charcoal particles are deposited nearby the fire and are not as easily suspended after deposition (Clark, 1988). For macro-charcoal analysis 86 (TD), 23 (GD) and 16 (TA) samples were prepared following the method described in Stevenson and Haberle (2005). For each sample 2 cm³ were used and wet-sieved at 125 μ m after chemical treatment. The samples of core TD were additionally sieved at 250 μ m to dispose of large organic remains. The complete remaining fraction was counted at 25 $\times$ magnification.

Results

Sediment characteristics and chronology

Core TD. The whole core consists of mud with max. 22 wt.% of material >63 μ m (Figure 2). The TC-values vary between 1.1 wt.% (45 cm) and 17.9 wt.% (543 cm, Figure 2). Planktonic foraminifera tests of fresh appearance occur between 571 and 503 cm, at 291 and 276 cm. The radiocarbon ages at 178 and 151 cm are 6020–6280 and 2790–2950 cal. yr BP, respectively (Table 3).

Core GD. The whole core predominantly consists of mud with $\leq$ 10 wt.% of very fine to fine sand throughout the core. Grains of coarse sand- to fine gravel-size enveloped by iron(hydr)oxide coatings occur between 100 and 90 cm (Figure 2). The TC-values range between 0.5 wt.% (68 cm) and 4.2 wt.% (203 cm, Figure 2). The radiocarbon ages at 213, 167, 112 and 80 cm are 6780–6700, 6290–6410, 5310–5470 and 6300–6440 cal. yr BP (Table 3). The

Figure 2. Columnar sections, mud (<63 µm) and total carbon contents of cores TD, GD and TA plotted against depth in metres below surface. Calibrated radiocarbon ages are given on the left of each core

age at 80 cm is older than the underlying one, implying that the uppermost part of the core contains reworked sediment.

Core TA. From 340 to c. 200 cm the core is composed of either very fine to fine sand (around 218 cm) or very sandy mud (50–70 wt.% mud). The remaining part of the core consists of > 90 wt.% mud. The TC-values range between 0.2 (major parts of the core) and 1.5 wt.% (top of the core, Figure 2). From 340 to 270 cm abundant shells and shell fragments from bivalves, gastropods, crustaceans, echinoderms, ostracods and foraminifera (mainly *Asterorotalia* sp.) are recorded. The radiocarbon age at 335 cm is 4440–4820 cal. yr BP (Table 3).

Pollen, spore and macro-charcoal records

The pollen, fern and fungal spore distribution as well as macro-charcoal records are shown in Figures 3, 4 and 5. The occurrence of *Pinus* pollen in all cores is ambiguous. It is possible that pollen from e.g. *Pinus merkusii*, a major component of the highland pine forests northeast of the delta (Schmid, 1974), were transported by wind over the long distance to the sites. Hence, the occurrence of *Pinus* pollen is excluded from the interpretation but added to the diagrams to represent a possible hinterland signal. Sedimentation rates beneath mangroves are highly variable (Woodroffe, 1992) and since erosion cannot be fully excluded, we refrained from evaluating the basal age of the lowermost pollen zones.

The northeastern MRD is known for its potential and actual acid sulphate soils (Husson et al., 2000). During the formation of these soils organic material (including pollen) is consumed in chemical redox processes (J Gröger, U Proske, TJJ Hanebuth, K Hamer and HD Schultz, unpublished data, 2010). The total pollen concentration values of all cores, however, are relatively high, showing that soil formation processes did not strongly affect the palynological signal. Other indicators for postdepositional alterations of the organic material are fungal spores. The abundance of fungal spores can be used as measure for the active decomposition of organic matter in the sediment (e.g. Almeida-Lenero et al., 2005). The abundance of fungal spores, however, is predominantly paralleled by high total pollen concentration values in the records indicating minimal decomposition of pollen by fungi.

Core TD

Zone TD-1 (574 to ~125 cm, early/mid Holocene to 2790–2950 cal. yr BP). The lowest zone in the core shows the predominance of *Rhizophora* pollen (71–96%) with minor contributions from *Ceripops* (≤ 10%), *Kandelia* (≤ 6%) and *Bruguiera* (≤ 3%). Additionally, the presence (≤ 5%) of other pollen of the mangrove community and freshwater vegetation is recorded. Values of total pollen and fungal spore concentration are on a moderate to low level. Macro-charcoal shows slightly higher values at the base and low values throughout the middle and the upper part of the zone. A marked decline of *Rhizophora* pollen (36%) occurs at 260 cm paralleling an increase in pollen of Arecaceae (16%), Fabaceae (9%), Elaeocarpaceae (7%) as well as total pollen and fern spore concentration.

Zone TD-2 (~125 to ~55 cm, 2790–2950 to 1150–1200 cal. yr BP). The second zone is characterised by a decrease in *Rhizophora* pollen percentages (11–32%) with marked increases in pollen of *Bruguiera* (≤ 7%), Arecaceae (≤ 23%), Cyperaceae (≤ 11%), Fabaceae (≤ 9%) and Poaceae (≤ 7%). Other pollen of the mangrove community and freshwater vegetation are present (≤ 5%). Values of total pollen, fungal and fern spore, *Acrostichum* sp., Polypodiaceae and macro-charcoal concentration show an abrupt increase and remain on a high or moderate level.

Zone TD-3 (~55 cm to top, 1150–1200 cal. yr BP to modern). The uppermost zone marks the complete disappearance of pollen of the mangrove community. Freshwater vegetation is dominated by pollen of Arecaceae (29%), Poaceae (20%), Cyperaceae (15%), Fabaceae (6%) and *Burmannia* (7%). Values of total pollen, fungal and fern spore concentration are low whereas Polypodiaceae show an increase. Macro-charcoal values further increase to the highest value in the core.

Core GD

From 465 to 355 cm core depth the sediment contained no pollen, spores and macro-charcoal. However, no information about the Holocene palaeoenvironment is lost since this part of the core represents the Late Pleistocene soil surface.

Figure 3. Pollen, fern and fungal spore, macro-charcoal (bars) and TC (line) diagrams for core TD. Percentages are derived from total pollen sum. Closed circles represent taxa that do not exceed 5% of total pollen sum and are used to show presence/absence

Figure 4. Pollen, fern and fungal spore, macro-charcoal (bars) and TC (line) diagrams for core GD. For explanation see Figure

Figure 5. Pollen, fern and fungal spore, macro-charcoal (bars) and TC (line) diagrams for core TA. For explanation see Figure

Zone GD-1 (355 to ~105 cm, early/mid Holocene to 5310–5470 cal. yr BP). The lowermost zone is dominated by pollen of *Rhizophora* (78–61%) with minor contributions from *Kandelia* ($\leq 6\%$), *Cyperaceae* ($\leq 11\%$) and *Poaceae* ($\leq 3\%$). Values of total pollen, fungal spore and Polypodiaceae concentration show an increase towards 255 cm where they reach a maximum and subsequently decrease towards the top of the zone. Fern spore concentration and macro-charcoal values are low throughout this zone.

Zone GD-2 (~105 to 70 cm, 5310–5470 to 3300–3400 cal. yr BP). The second zone marks the gradual decrease of *Rhizophora* pollen (35–44%) paralleling an increase in pollen of *Kandelia* (13%), *Cyperaceae* ($\leq 15\%$), *Fabaceae* ($\leq 4\%$) and other freshwater vegetation elements. Other pollen of the mangrove community and freshwater vegetation are present ($\leq 5\%$). Values of total pollen concentration are on a moderate level, fungal and fern spores, Polypodiaceae and macro-charcoal concentrations are low in this zone.

Zone GD-3 (70 cm to top, 3300–3400 cal. yr BP to modern). The uppermost zone is characterised by the further decline of *Rhizophora* pollen ($\leq 6\%$) and pollen of *Kandelia* reach the highest value (18%) followed by a decrease to very low values ($\leq 5\%$) at ~55 cm. Freshwater vegetation mainly represented by pollen of *Fabaceae* ($\leq 34\%$), *Poaceae* ($\leq 29\%$), *Cyperaceae* ($\leq 24\%$) and *Myrsinaceae* ($\leq 8\%$) dominates the record. Values of total pollen, fungal and fern spores, Polypodiaceae and macro-charcoal increase with some reaching their maxima within the record. The occurrence of *Azolla* spores is recorded at the top of the zone.

Core TA

Zone TA-1 (340 to 230 cm, 4440–4820 to 2950–3300 cal. yr BP). The lowermost zone is dominated by pollen of *Rhizophora* ($\leq 50\%$), *Bruguiera* and *Ceriops* ($\leq 8\%$). Freshwater vegetation is represented by pollen of *Moraceae/Urticaceae* ($\leq 16\%$), *Cyperaceae* ($\leq 5\%$) and *Poaceae* ($\leq 4\%$). Values of total pollen, fungal and fern spore, Polypodiaceae and macro-charcoal concentration are low.

Zone TA-2 (230 to ~108 cm, 2950–3300 to 1500–1600 cal. yr BP). The second zone marks the decrease in pollen of *Rhizophora* ($\leq 35\%$) and *Bruguiera* and *Ceriops* ($\leq 6\%$). Towards the top of the zone pollen of *Kandelia* ($\leq 14\%$), *Moraceae/Urticaceae* ($\leq 18\%$), *Fabaceae* ($\leq 15\%$), *Cyperaceae* ($\leq 10\%$) and *Poaceae* ($\leq 10\%$) increase whereas *Moraceae/Urticaceae* show a maximum at the base of the zone. Total pollen and fungal spore concentration values are highest at the base of the zone and decrease towards the top. Fern spores, Polypodiaceae and macro-charcoal concentration values are on a medium to low level throughout.

Zone TA-3 (~108 to top, 1500–1600 cal. yr BP to modern). The sample at 77 cm core depth contained no pollen and spores. The uppermost zone is completely characterised by pollen of freshwater vegetation such as *Cyperaceae* ($\leq 43\%$), *Poaceae* ($\leq 29\%$), *Sagittaria* ($\leq 31\%$) and *Moraceae/Urticaceae* ($\leq 9\%$). Total pollen and fungal spore concentration values increase towards the top. Fern spores and Polypodiaceae concentration values remain on a medium to low level throughout. Macro-charcoal concentration shows high values at the base and at the top of the zone.

Figure 6. (A) Columnar sections showing interpreted general vegetation zones for all cores. Measured calibrated radiocarbon ages are marked with an asterisk, calculated age spans with an open circle (see text). (B) and (C) Palaeoenvironmental development of the region illustrated by the time spans for the transition inner to back-mangrove (B) and subsequently to freshwater vegetation (C). The base map is simplified and dimmed from Nguyen *et al.* (2000). The thick, black lines mark the coastlines with corresponding time spans after Nguyen *et al.* (2000). The coastlines 4.5 and 4–3k yr BP are widely unconfirmed (dashed line, see Nguyen *et al.* (2000) for details). The asterisk marks time spans directly controlled by calibrated radiocarbon ages, the open circle marks calculated time spans (see text)

Discussion

The palaeoenvironment in the early to mid Holocene

During the mid-Holocene when sea level was between *c.* 2.5 and 4.5 m above present level (Ta *et al.*, 2002a, b), a broad mangrove belt was established along numerous coasts of the Sunda and Sahul shelves (Woodroffe, 1993, 2000; Woodroffe *et al.*, 1985). The *Rhizophora*-dominated mangrove forests of the northern delta were part of this belt fringing the coastline and river banks as far north as Phnom Penh (Penny, 2006, 2008; Tamura *et al.*, 2009). The palynological records of cores TD and GD indicate that mangrove forests were also widespread throughout the northeastern MRD (zones TD-1 and GD-1, Figures 3, 4 and 6A). High percentages of *Rhizophora* pollen mark their strong presence at the sites and the occurrence of *Avicennia*, *Sonneratia*, *Bruguiera*, *Ceriops*, *Kandelia* and *Aegiceras* indicate a distinct zonation of these forests. The relatively low macro-charcoal values mark an overall irregular and infrequent, natural burning of the regional vegetation. More intense burning could be mirrored in the slightly elevated charcoal values coinciding with minor abundant Poaceae pollen (1–2%) in the lowermost *c.* 0.5 m of zone TD-1 (Figure 3). A similar signal from northeastern Cambodia has been related to drier conditions leading to frequent burning of the local to regional vegetation between 9300 and 7900 yr BP (Maxwell, 2004).

At sites TD and GD mangrove deposits are thick (4.5 and 2.55 m, respectively, Figure 6A) implying either a fast sediment build-up during the sea-level highstand or the onset of accumulation already during the late stage of the postglacial transgression. Mangrove peat accretion in a thriving forest can keep pace with a 2 to 10 mm/yr sea-level rise (Ellison, 2008). The oldest mangrove deposits from southern Cambodia accumulated *c.* 8000 yr BP (Tamura *et al.*, 2009) when sea level was *c.* 5 m below modern level (Tamura *et al.*, 2009). From 8000 to 6000 cal. yr BP sea level rose at an average of 3–4 mm/yr, which could have been balanced

by sediment accumulation beneath the mangrove forests. Thus mangrove forests probably established already during the early mid-Holocene in the northern parts of the delta and dominated the coastal landscape during the late transgression.

The short-term decline in *Rhizophora* pollen at 262 cm in core TD (TD-1, Figure 3) is paralleled by an increase in freshwater taxa (mainly Arecaceae, Fabaceae, Elaeocarpaceae and ferns). An intense fire event in the mangrove forest can be excluded since macro-charcoal concentration is not increased. Various other observations, however, imply a brief and intense disturbance of the site. First, the higher total pollen concentration value at 262 cm indicates a temporarily lowered sedimentation rate. Second, below the decline in *Rhizophora* pollen (between 302 and 280 cm) the sediment appears chaotic and contrasts the under- and overlying slightly laminated sediments. And third, the samples at 291 and 276 cm contain fresh and unbroken planktonic foraminifera tests that have not been detected in other samples directly above or below this interval. These features imply a temporary disturbance of the site as it could be expected by a storm- or typhoon-induced flood event. Such a short-term, high-energy event is able to damage the coastal vegetation, transport shallow marine shelf sediments (including foraminifera) landwards and thus produce deposits with the features described above. After the event, the hinterland pollen signal would be enhanced and sedimentation rate would be lowered owing to sparse mangrove presence and thus decreased sediment trapping at the site. Since there are no gap specialists in mangrove communities (Clarke and Kerrigan, 2000), the affected area would be gradually recolonized by species from the surrounding, intact mangrove forest. This recolonization is probably reflected in the stepwise recovery of *Rhizophora*, the decline of *Kandelia* and the increase of *Avicennia* and *Ceriops* (Figure 3). A similar signal is absent at site GD being either due to its geographical position where the elevated Pleistocene terraces shelter the area from the prevailing northeasterly storms or the sample resolution being too low to detect this decline.

Palaeoenvironmental development in the late Holocene

The regional development after *c.* 4500 cal. yr BP is characterized by the establishment of back-mangrove and freshwater vegetation in the northeastern MRD. By assuming a constant sedimentation rate after the mid Holocene and by using the 2σ -ranges of the calibrated age data it is possible to calculate time spans for the changes in vegetation where no radiocarbon dates are available (Figure 6A). Two transitions are established for each core: from inner mangrove to back-mangrove (Zone 1 to 2, Figures 3 to 6A) and subsequently to freshwater vegetation (Zone 2 to 3, Figures 3 to 6A).

At the westernmost site GD the back-mangrove signal is mainly composed of *Kandelia*, *Bruguiera*, *Ceriops* and *Avicennia* (Figure 4, GD-2) indicating that saltwater influence in the area is limited to flooding during high tide. Other back-mangrove elements such as *Phoenix*, *Excoecaria* and *Heritiera* are present in the region already since the early mid-Holocene but show no increased abundance at this stage. The radiocarbon ages imply that back-mangrove established directly after the mid-Holocene sea-level highstand in the area around site GD which indicates a very fast seaward coastline migration (Figure 6B). However, the uppermost calibrated radiocarbon age shows inversion as a result of sediment mixing or bioturbation in this part of the core and thus leaves the time frame for the development from mangrove to freshwater vegetation in the area around this site unclear.

At site TD the back-mangrove signal is dominated by *Ceriops*, *Bruguiera*, *Heritiera*, *Excoecaria*, *Glochidion*, *Phoenix* and *Acrostichum* marking the decreasing influence of saltwater in the area around 3000 cal. yr BP (Figures 3 and 6A, TD-2). Increased total pollen and fern spore concentration values indicate a lower sedimentation rate as it is typical for the floodplain environment where sediment is supplied only during the annual summer monsoonal flooding. In this area the back-mangrove established relatively late when the coastline was already *c.* 30 km further south (Nguyen *et al.*, 2000 and Figure 6B). To support the mangrove community along the river banks, sufficient seawater must have been transported upstream in the Vam Co Tay River which can be achieved by tidal pumping. In the modern southern MRD this effect is commonly observed and mangroves grow along rivers as far as 90 km inland today (Hong and San, 1993). In zone TD-2 macro-charcoal values increase rapidly being either due to intense burning of the local, more open vegetation or the beginning of human settling accompanied by fires in the region. The radiocarbon age and the archaeological record for the area imply that this charcoal signal could be linked to ancient settlers but natural fires cannot be fully excluded.

The southernmost site TA shows a generally weak *Rhizophora* signal implying that the local conditions were not suitable to support mangroves directly in the area around the site. The lowermost zone (Figure 5, TA-1), however, is dominated by the sum of *Rhizophora*, *Bruguiera*, *Ceriops*, *Sonneratia* and *Aegiceras* marking a zoned mangrove forest in the general region during the sea-level regression. The coeval strong signal from freshwater forest and grassland/swamp elements such as *Moraceae*/*Urticaceae*, *Poaceae*, *Cyperaceae* and *Fabaceae* reflects the geomorphological diversity of the delta plain (Figure 6B,C) and underlines that freshwater vegetation is already common in the area. The representation of a back-mangrove (mainly *Kandelia*) is weak and probably a result of the conditions in the area that prevented an extensive mangrove development. The change from inner to back-mangrove has been calculated between 2950 and 3300 cal. yr BP and thus has to be

viewed with caution (Figure 6B). Around 3000 to 2000 yr BP the reconstructed position of the coastline is just south of the site (Nguyen *et al.*, 2000), which indicates either a very fast vanishing of the inner mangroves or the calculated age span is too old.

At all sites, the subsequent shift from back-mangrove to freshwater vegetation is consistent with the coastline evolution (Figure 6C). The general, typical signature of swamp vegetation is dominated by *Cyperaceae*, *Fabaceae* and *Poaceae*. At site GD the transition from back-mangrove to freshwater around 3300–3400 cal. yr BP is problematic owing to the inversion of the uppermost two radiocarbon ages. Nevertheless the freshwater vegetation shows a varying composition with *Myrsinaceae* adding a forest to shrub land signal and *Azolla* spores, occurring in the uppermost sample and being associated with modern rice cultivation (Schmid, 1974), mark the establishment of agriculture in the area around this site. The simultaneous increase in macro-charcoal particles underlines that modern settlers were reshaping the environment of the site.

Arecaceae and the freshwater swamp marker *Burmannia* are remarkably common at site TD, indicating that the river floodplain is a moist habitat throughout the year (Schmid, 1974). High amounts of macro-charcoal particles imply the presence of settlers in the area and the rise in *Arecaceae* pollen could be linked to an active cultivation of palms.

Site TA records a short-term occurrence of *Sagittaria*, an aquatic to riparian genus. It seems that a small, temporary lake or channel established in the vicinity of the Vam Co Tay River, providing the temporary habitat for this genus. However, this lake or channel prevailed not long enough to support full aquatic vegetation. Similar to the two other cores a strong macro-charcoal signal documents the increased human activity in the region.

Conclusions

The palaeoenvironmental reconstruction of the northeastern MRD underlines the dynamics of the delta development since the mid Holocene. An inner mangrove community moved with the seaward migrating shoreline and was gradually replaced by back-mangroves. The back-mangrove forests seem to have prevailed for a long time especially along rivers that supplied brackish water. Finally, diverse freshwater vegetation developed on the MRD plain. Natural burning of the regional vegetation is recorded in the low abundance of macro-charcoal particles in the lower parts of all records whereas the high values in the uppermost parts of the records document the modern human activity.

Furthermore this study shows that palynological techniques, being optimised for swamp and lake deposits, are also applicable to dynamic delta deposits that have been subjected to soil formation processes. The results demonstrate the importance of palynological studies to fully assess a delta's palaeoenvironmental development. This palaeoenvironmental reconstruction also offers the opportunity for archaeological researchers to add new information to the understanding of ancient settlements in the region.

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